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VARIABILITY, NON-UNIFORMITY, AND COMPLEXITY: FROM PRODUCT TO PROCESS

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1. INTRODUCTION

The variability in process and product is part of our life in the industry. For example, in the headbox jet speed and temperature are constantly changing at different frequencies; cross-machine direction elastic stiffness has a typical inverse-smile pattern across the paper machine width; qualities of pulp bale often vary from one shipment to the other. For many years, the industry has been tackling this problem in different unit processes. Particularly in today's competitive market, achieving consistency and uniformity is a necessary condition for staying in the market. Accordingly the subject has been heavily investigated in process control area in terms of control methods (adaptive control, multivariable control, and expert system), sensor developments, and process control is provided in [1-2].)

This review paper deals with the same subject but from a slightly different angle, i.e., performance perspective. In the beginning, it may not be obvious why performance problems are those of variability and non-uniformity. However, this problem almost always emerges as a central theme at the end. More importantly, we find that the problem is not a mere manufacturing or product quality problem, but has profound impacts on the industry's fundamental cost structure and profitability. This subject is undeniably complex. However, we first try to illustrate a few anecdotal examples that might suggest such fundamental problems behind.

Now and then, mill process engineers find a wrong input of a set value for kraft content for reinforcement in paper machine operation. As a result the machine has

been running with, say, a 5% lower kraft content, for a long time period. However, strangely, operators have noticed no single problem during that time period. Similar examples exist for a paper machine mistakenly running with much higher filler content, but again without any problem. These observations are not uncommon. A natural question is why supposed-to-be weak stocks can run well, or even better than stronger stocks, on paper machines. If it is possible to continue this fortunate status routinely, the cost consequence is enormous.

A similar example may be found in corrugated box design. Corrugated boxes are designed based on the strength/stiffness values of linerboards and flutes, together with empirical safety-factors considering end-use conditions. Apart from this industry's practice, creep lifetime measurements have been performed in the literature for many years, as they are believed to represent real end-use conditions better than normal strength. The results are rather disturbing: at a given box (or at a given average box strength), the coefficient of variation of life time is in the order of 70% to 90%! An observation also showed that, with the average lifetime more than 20 days, it is still not unusual to find a few outliers of lifetime of about only 2 days. If we can eliminate these few outliers, we can make a massive improvement of end-use performance, without costing more fibres (basis weight), more chemicals (strength additives), and more energy (refining and thus drying).

Another example is in product development. It is sometimes observed that paper with best formation somehow happened to be the worst performer (in fluting) in heatset offset printing. On the other hand, it was also observed that one with rougher surface and worse formation doesn't necessarily perform worse in barrier coating. Such (confusing) experiences abound in new product development. If we can find a red thread in paper variability in micro-scales, we can accelerate our process of product innovation tremendously. As many experts admit, product development is a constant battle with variability and nonuniformity.

In this paper we have chosen several of the performance issues and have tried to make a consistent review of the efforts made in the literature from the stand point of variability and non-uniformity. Each area has its breadth and depth, and clearly deserves its own review paper. Therefore, the author must admit that this review paper is far from comprehensive. However, he has tried to find a red thread toward the problem of variability and non-uniformity from a vast amount of information, so that the readers can receive a coherent story. Lastly, we would like to touch upon the concept of complex system. Complex system is an emerging area of science, and, perhaps, is becoming increasingly relevant to today's world. In fact, as we may find, many of the issues related to performance, variability, and non-uniformity is an aspect of complex system problems.

(In this review, we have used the word *variability* mainly for referring to temporal variations, and *non-uniformity* to spatial variations.)

2. PROBLEM DEFINITION

Variability and non-uniformity are almost an inherent nature of pulp and paper making processes. Figure 1 illustrates a typical manufacturing chain of the industry.

Today pulp and paper mills rarely receive a single wood species, but usually a few or several species for production. Even if a single species is received in the mill, it might be collected from different parts of the forest lands, which may contain juvenile and mature woods, for example. These woods normally have different fibre lengths and cell wall geometries (e.g., fibril angles in S2 wall), and thus result in different properties in end-products [3–7]. This variability is only the very beginning of the entire manufacturing chain. As these woods go through chippers, chemical/ mechanical pulping processes, bleaching process, and refining processes, they receive treatments with different set points in control, resulting in pulp fibres with different Kappa numbers, viscosities, brightness values, fibre lengths, and freeness values. In addition, these output values from the upstream processes in paper mill fluctuate with time, depending on the performance of control loops involved (Fig. 1). What may be more important is that these pulps produced are highly heterogeneous on the individual fibre level. Fibre lengths are, of course, different, but the properties, such as flexibility, strength, and cell wall damages, may vary tremendously, as these fibres went through highly heterogeneous processes, such as mechanical pulp refiners. As the pulps are prepared as papermaking stocks and transported to paper machine, they become a suspension of a wider spectrum of heterogeneous particles (fibres, fillers and other colloidal particles), receiving similar fluctuations from the process, such as those of concentration, composition, and temperature. The paper machine, of course, adds the fluctuations of jet speed,



Figure 1. Process variability and product performance.

draw, press/calender loading, dryer steam, etc. with time as well as in the cross machine direction (CD non-uniformity). Nevertheless the products that come out of these processes are amazingly "uniform" in terms of meeting basic specifications, such as basis weight, thickness, moisture content, and other mechanical and physical properties. This is, of course, owing to today's process control systems.

A real question of variability and non-uniformity often comes from the end of this manufacturing chain, product performance in end-use. Product performance is a multi-faceted property. It is often not represented by a standard set of product specifications, but is, instead, expressed by vaguely defined words, such as runnability, durability, and softness, for example. These performances are normally a *system* property, and never are a function of a single property, such as strength and surface roughness, as we will see in the subsequent sections. Therefore, in order to enhance performance, i.e., what customers see as values, it is important to understand the properties of product performance (System B in Fig. 1) first, and then to approach to the process variables (downstream to upstream approach). Otherwise it is extremely difficult to resolve problems by investigating impacts of one process variables on the performance (upstream to downstream), because a change in one process variable in the upstream normally requires subsequent changes in the multiple process variables in the downstream.

Although it is not obvious in the beginning, these performance problems are almost *always* related to the variability and non-uniformity of paper structures and properties, and thus to pulp and papermaking processes. It is known that a variability spectrum, in length or frequency, of pulp and papermaking process is extremely wide, such as shown in Fig. 2 [8]. The smallest length scale may be those for fibres, 1–3 mm, and the longest scale may be 40–50 km for a jumbo reel. However, some of the performance issues are related to even smaller length scales, such as agglomerations of filler pigments which are in micron scales, or to even longer, such as seasonal variations of wood fibre stocks which are in a several-month scale. As we see in the following sections, the variability of micro-scale structures often appears as a stumbling block to resolve some of the very difficult performance issues. This is a reflection of the fact that our current manufacturing technology still can't control such small-scale structures. (Theoretical developments for describing random fibre network structures are reviewed in [9].)

3. PERFORMANCE ISSUES AS RELATED TO VARIABILITY AND NON-UNIFORMITY

3.1 Web breaks in printing house

Runnability of paper in printing presses, particularly web break, is probably one of the most investigated subjects in pulp and paper industry. Regardless of whether



Figure 2. Variability spectrum of paper machine at 1000 m/min [8].

it is the problems for printing paper or packaging grades, it is an undeniable fact that runnability is the main concern for developing today's specifications for pulp/ paper strength, such as (average) tensile, tear, burst, and TEA. A far more important fact is that these specifications have determined the cost structure for paper production since the inception of products developed. Therefore a relevant question may be whether these specifications are still meaningful today to meet the end-use performance at minimum cost.

Web breaks are rare phenomena [10]. Suppose paper web breaks at an average rate of 3 breaks per 100 rolls, and assuming 40 inch diameter rolls are run, we find break events at every 350 km of paper web! Accordingly a monthly break statistics in printing house has been known to fluctuate immensely [11]. From early days of research, it has been recognised that breaks are almost a random process, i.e., the event happens randomly along the time axis (Poisson process) [10]. The implication of this is that seeking a cause-effect relationship for each event is extremely difficult, if not impossible. Secondly, from a practical view point, comparing runnability performance among different paper suppliers has great uncertainty. Suppose an average break rate is 2% and 500 rolls are consumed by a printing house every month, a range of 95% confidence interval for the monthly

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break rate is from 0.7% to almost 4% [12]. This means that it is almost impossible to compare monthly runnability performance among paper suppliers in a small printing house [13]. The variability of performance data is an inherent nature of extreme statistical phenomena.

Then how to find break causes? Since the individual fact-finding is difficult, except a few most obvious cases, such as dropping objects on paper web or missing splices, researchers today have taken large data base from printing houses and paper mills to find potential break causes. The conclusion is that the majority of breaks are actually caused by printing press-related issues [14-15], such as pasting-cycle errors, tension control, problem units (nip control), and mechanical/ electrical breakdown [12] (Fig. 3). The second largest cause is often "unknown". When operators are not forced to assign each break event to specific causes, the most honest answer is "unknown". As described later, this is where an important subject of variability emerges. The third largest is wrinkles and creases [16]. This is due to a well-known, non-uniformity issue, web tension non-uniformity of paper web, which will be discussed later. Other typical defects in paper were actually minority causes in break statistics [16]. In earlier studies [17–18], however, paper defects (e.g., holes, cuts, and shieves) were shown, through *pilot-scale* studies, to be the major causes for breaks. This tempted many researchers later to investigate effects of defects (for example [19–26]) and fracture mechanics of paper web. (For example, the historical aspect of fracture mechanics of paper is



Figure 3. Break cause statistics of heatset offset printing house [16].

reviewed in [27]). The main conclusion from these theoretical and experimental studies is that, in order to see web breaks at a realistic tension level, it requires very large cracks, such as 4–8 cm horizontal cracks. This means that, in a normal operation, the web transport system (e.g., printing press) is very tolerant to such defects in paper. This was confirmed by meticulous studies using special optics and web inspection systems [28–29]: they showed that most of the breaks are not uniquely related to the presence of obvious defects, and many of the breaks have "unknown" causes.

A common concept for explaining unknown breaks may be to consider break as a combined probabilistic event of high tension and low strength, such as depicted in Fig.4. Accordingly, the variability of both tension and strength is important, in addition to their average values. Although the interpretations of tension variability and strength variability still require careful examinations, as we will do below, the concept is simple and has begun to be accepted in the industry in recent days.

Tension (or tensile stress) varies both spatially and temporally [30–31], and at low/high frequencies [32–34]. For example web tension non-uniformity across the roll width has recently attracted acute attention in relation to web breaks. A well-known problem is a baggy roll, in which web tension at one edge is significantly lower than the other; this non-uniformity of web tension creates various instability problems in web transport systems. (We will discuss the subject later.) Another example of the spatial variations is in a smaller scale, i.e., stress distributions within the printing nip [35]. In an offset printing press, when paper web is compressed by a deformable blanket, it is stretched (or extruded) in the inplane directions (the machine and cross-machine directions) due to Poisson effect (See Fig.5).



Figure 4. Break as a combined probabilistic event of high tension and low strength.



Figure 5. Distribution of machine-direction strain along the nip centre line. High strain concentration at the paper edges [35].

Because of the boundary conditions applied, this tensile strain (in the machine direction) varies in the cross machine direction. Particularly at both edges of the printing roll, the stress is elevated and could exceed even the yield strain (~ 0.2 %) of paper web, depending on the configuration and mechanical properties of the blankets used [36]. Unfortunately, such tensile stress spikes within the printing nips can't be observed by any of the tension measurement systems. Tension also varies with time due to draw variations. (Draw is a relative speed difference between the in-feed web and out-feed web, or in-feed and out-feed rolls.) The higher the draw, the higher the tension generally. Draw variations, however, contain specific high/low frequency components as well as white noises. The specific peaks in the power spectrum can be traced back to the vibrations of specific rotational components of printing press [32]. Web dynamics analyses showed that, in a free span section between a set of nipped rolls, high frequency draw variations tend to be filtered out at a certain frequency [33], and, higher frequency components are not translated into higher tension variations. This frequency is called characteristic frequency, and it depends on the span length and web speed, and thus it is dependent on printing press and its operation. The relationships between draw variations of printing press and web breaks have been found recently by using two-point Doppler speed measurements [32]: The higher the standard deviation of draw, the more frequent the web breaks (Fig. 6). It is apparent that tension (tensile stress) variations in the web transport systems often have a dominant effect on web runnability.

Another important factor is strength distribution. Although the concept depicted in Fig. 4 is straightforward, for practical applications, it requires some fundamental consideration.

The first question is what strength is relevant. There have been long debates on the relevancy of tensile strength and tear strength, and also fracture toughness



Figure 6. Breaks in printing house, as affected by draw variation (STD: standard deviation of draw) [32].

(in-plane and out-of-plane) both in the industry and in the research community (for example, [37–39]). Fracture toughness is, in general, regarded as crackextension resistance of the material which contains macroscopic stress concentration sources (e.g., cracks, cuts, holes, and angle bars in printing presses). In this sense tear strength is classified as one of the fracture toughness parameters (Mode 3), although it is difficult to interpret tear strength in a standard fracture mechanics term. Therefore, these parameters are relevant when web breaks are driven by pre-existing macroscopic defects. On the other hand, for those "unknown" breaks, with no obvious defects or stress concentration sources (except microscopic disorder), tensile strength is more relevant. The results based on extensive data mining of 20,000 to 50,000 rolls [16, 28, 34] did show that (average) tensile strength consistently predicts web breaks, whereas tear strength does not. In-plane fracture toughness was also shown to be correlated to web breaks from a large set of data [10], as it is related to tensile strength and stretch (for example, [40]). Therefore, for those unknown breaks in printing presses, tensile strength is the best approximation of the relevant strength property. (We will later discuss about stretch property.)

The second question may be more intricate: at which size the strength should be considered. Strength is generally dependent on the size of the specimen. It is believed that the larger the size, the weaker the specimen, because failure tends to occur at a weakest spot (weakest link hypothesis [41-43]). A typical example is the failure of a 1D chain structure. However, this is not generally true for disordered materials which span their structures in a 3D space. Particularly in a small

specimen whose size is not sufficiently large as compared with its structural unit size, the weakest link hypothesis is no longer valid; strength can increase or stay the same with increasing the size of the specimen, and the problem has been investigated heavily in statistical mechanics literature [44–51]. The main conclusion is that, for a brittle system, this weakest-link type failure mode appears only after the specimen size exceeds a critical size. This is normally confirmed by observing the scaling behavior of cumulative distribution function of strength. The corresponding behavior is called weakest-link scaling. In the case of paper, it was found that this critical size is in the order of 1.5 to 2.0 cm [52], which happens to be the minimum size (width) of tensile specimen. Therefore, the specimen size used for standard tensile testing is appropriate (and convenient) for investigating tensile strength distributions. Specific sampling issues are discussed in [53].

The distribution form of tensile strength is obviously the main question. Extreme value statistics, which deals with extreme phenomena such as materials failure and stock crash, offers three potential distributions (Gumbel, Fréchet, and Weibull distributions) [54]. In experimental mechanics and reliability engineering literature, Weibull distribution is favoured and it fits well to experimental data [55-56] in many cases. However, for general disordered materials, Weibull distribution is not an obvious choice. For example, depending on the assumed distribution shapes of pre-existing micro-cracks, there are two potential distributions, Weibull and double exponential distributions [47, 57-59]. From the context of fibre networks, even if the weakest-link scaling holds, the asymptotic distribution of fibre-bundle networks, for example, is not of Weibull type [49, 60]. However, extensive numerical and analytical studies [61–63] found that (1) the asymptotic distribution can be approximated by Weibull distribution in a piece-wise manner, and (2) in practice, as the range of probability values that can be observed experimentally is always limited, it is normally difficult to discern any significant deviation from the piece-wise Weibull approximation. In other words, the ubiquitous nature of Weibull distribution as a model for strength distribution is partly accidental, but originates from the unique mathematical properties of the algebraic form function [45]. It was also shown that approximating strength distributions with Weibull distribution provides an upper bound of the tail distribution of strength [52]. In other words, using the Weibull approximation to predict web breaks gives a conservative (safer) estimate of failure risk.

Given the distributions of tensile strength and tension, one can obtain an expression for the break frequency n (for example, the number of breaks per 100 rolls) [34, 53, 64] as follows:

$$n = k \cdot \langle \left(\frac{T_0}{T_{MD}} + \frac{\Delta \varepsilon_{max}(L)}{\varepsilon_{MD}}\right)^m \rangle_L,\tag{1}$$

where k is a constant related to the roll size and the specimen size used for evaluating strength distribution. In the above equation there are two sets of parameters. One set is related to printing press: T_0 is a set tension in printing press, and $\Delta \varepsilon_{max}$ is maximum strain (from a set value) that the paper web would experience in running through the entire press length L. In other words, the latter concerns tension (tensile stress) variations. The operator $\langle \cdot \rangle_{L}$ denotes the operation of taking expectation of the random variable $\Delta \varepsilon_{max}$ along the press length L. The other set is related to paper properties: T_{MD} and ε_{MD} are average (median) tensile strength and stretch, m is a uniformity parameter (Weibull shape parameter) of strength distribution. (The higher the m, the more uniform the strength.) Inspecting the above equation reveals that both tension and strength variability is coupled through the strength uniformity parameter m, affecting web break frequency. The uniformity parameter typically varied from one paper machine to another between 12 and 22 [16, 64]. This implies a significant room for improving strength uniformity in papermaking. Figure 7 shows a relationship between break frequency and the uniformity parameter m for a specific printing house and a specific paper supplier [16]. In this figure the break frequency includes non only unknown breaks but also press-related breaks. One can clearly see a dramatic reduction of break frequency by enhancing paper uniformity. (During this data collection, there was no change in average strength.)

The most important question may be how to enhance strength uniformity in the pulp and papermaking processes. Surprisingly the published data is very scarce. It is partly because the information is strategically critical for individual mills, and



Figure 7. Break rate against uniformity parameter in a printing house for one paper supplier [16].

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also because the majority of the studies concern the improvement of "average" strength rather than uniformity. Formation, as interpreted as mass-density distribution, has been well-known to have influences on (average) strength (for example, [65–68]). Particularly when headbox consistency is lowered, average strength clearly increased. However, it was not clear how the strength uniformity is affected by the formation change. A recent study showed that when the consistency of the suspension is lowered, the strength uniformity parameter (Weibull shape parameter) increased sensitively (more uniform), whereas when formation is changed by forming conditions other than the headbox consistency, there was no significant relation between formation and strength uniformity [69]. A recent pilot-scale study using a web strainer also investigated effects of various papermaking variables on strength uniformity [70]. Results showed that basis weight, CD position, and reinforcement pulp type clearly influenced the uniformity parameter.

3.2 Wrinkles, web weaving, and edge-fluttering

These phenomena are commonly seen in any web transport systems, such as paper machine, winder, converting machine, and printing press. Wrinkle often happens when paper web passes through a roller nip. As paper web can't withstand compressive stress, any misalignment of the transport direction, which is caused either by the system or by the paper web, can trigger wrinkles [71–72]. The most notorious cause, on the paper side, is web tension no-uniformity, i.e., web tension is not uniform across the paper width. It is sometimes called baggy edges, since lower web tension tends to occur (not always) at both edges of the paper machine width. Another related phenomenon is web weaving (or web wandering), which is often seen in winder and printing press. In this case the web tension non-uniformity varies along the machine direction [73-74]. Edge fluttering, as typically seen in a paper machine dryer, has compounded causes, including pre-existing vibrations of rotating elements and tension variations from other causes. However, the recent web dynamics studies showed that web tension non-uniformity has an overwhelming effect on edgefluttering [75–77].

Systems for measuring local web tension have been developed for the last 30 years [30, 78–86], and the presence and importance of web tension nonuniformity are now recognized by many paper engineers. Accordingly, these instrumental studies are focusing on finding the causes of web tension nonuniformity in papermaking process.

One factor is the non-uniform CD moisture profile often seen at dry end of papermaking process: Areas where the moisture content is high have lower web tension [87]. However, it was also found in many mill trials that, without any

significant non-uniformity of moisture profile, web tension can still be very nonuniform. Tensile stiffness is also often quoted as a cause of web tension nonuniformity [72, 81], but, again, it was not always the case. As web tension problems often appear as baggy edge problems, the CD shrinkage profile in the dryer section has been suspected as a culprit by many researchers. Effects of drying shrinkage at both machine edges on the non-uniform CD profiles of tensile stiffness, stretch and also hygroexpansivity have been investigated intensively over the years [88–93]. Today shrinkage profiles can be determined on machines, and resulted CD profiles of tensile stiffness and stretch can be predicted by a practical empirical equation. A finite element analysis has been performed for a wide web subjected to tension and hygro-shrinkage. The result showed a typical pattern of lower tension at edges [94]. However, it has been also observed in the fields that lower web tension occurs not only in the machine edges, but also in non-edge areas. The most interesting observation is that, regardless of the final moisture profile at dry end, steam shower applied in the press section has a significant impact on web tension uniformity. (See Figure 8 [94].) Since, in wet-end,



Figure 8. Cross-machine direction profiles of web tension, tensile stiffness, and moisture content [94].

paper web is more deformable to applied forces, depending on its moisture content, a drying *history* has been suggested as an important factor in considering web tension non-uniformity [95–96]. Another important factor is super-calendering [74]. The compression applied in calendaring makes the paper expands in the in-plane direction by Poisson effect. Therefore, the profiles in calendaring pressure and steam applied at calendar directly affected web tension uniformity.

In order to put these experimental and trial results in a context, we may express web tension in a general format, such as follows:

$$T(x) = C_{11}(x)(\varepsilon_{0,11} - \beta_{11}(x) \cdot \Delta m(x) - \gamma_{11}(x)),$$
(2)

where T is web tension (per unit width) in the machine direction and it depends on a position x in the cross machine direction (i.e., web tension non-uniformity). C₁₁ is the corresponding elastic stiffness in the machine direction, which also varies with the position x, typically due to non-uniform fibre orientation profiles across the machine width. In the parenthesis, there are three strain components: the first component is an applied strain which is normally uniform across the width. The second is hygro-expansion (shrinkage) strain caused by moisture change from a reference state, with β hygro-expansion coefficient. The third is natural strain (or residual strain) which is present even under tension-free conditions. These components are, of course, position-dependent. It is clear from this simple consideration that, first, the stiffness and moisture profiles $(C_{11}(x) \text{ and } \Delta m(x))$ affect the web tension uniformity. The hygroexpansion coefficient $\beta_{11}(x)$, however, may not vary much across the machine width as compared with its counterpart in the cross machine direction, as there is no shrinkage in the machine direction. The most influential part is the natural strain component $\gamma_{11}(x)$, which is created by the non-uniformity of compression (pressing, calendaring) and by drawing the web with non-uniform CD moisture profile in the press and dryer sections. The effects of steam shower in the press section and super-calendering are mainly represented by this component $\gamma_{11}(x)$.

The above equation represents the contributions from the components only in the machine direction, and no cross elasticity effects from the similar component in the cross machine direction. Nevertheless, it already depicts the complexity of web-tension uniformity issues, as related to various non-uniformity issues in paper making process. It should also be noted that the order of magnitude in strain related to web tension uniformity is very small, usually in the order of less than 0.1 % difference across the roll width. This signifies the extremely high level of today's uniformity demands from the market.

3.3 Runnability on paper machine

The problem of wet-end breaks on paper machine is very similar to the one in printing press in terms of problem structure. There is a great effect of web tension control and its variations, so called "paper machine operation". There is also an effect of strength, in this case, wet strength and its variations. The only difference may be that direct data of wet strength variations on paper machine are very scarce or not available.

Figure 9 shows an example of monthly break statistics in a Japanese paper mill in 1990s [97]. Break frequency considerably varied from one month to another, and also showed a systematic reduction after a certain time. It is interesting to note that these reported break frequencies (e.g., mostly much less than 30 breaks per month) are much lower than the corresponding values in North America and Europe (i.e., more than 60 breaks per month).

The break cause statistics also varied over the years. In 1980s and 90s, dirt (e.g., stickies) and defects associated with the undesirable deposits have been identified as one of the most prominent causes of web breaks in paper machine (e.g., [98–99]). This identification partly owes the development of high-speed, high-resolution cameras in paper machine. Accordingly, many paper mills adopted a regular and stricter cleaning program of the papermaking system since then to reduce breaks. Although there are still occasional outbreaks of dirt/sticky related breaks, the current overall breaks statistics shows non-obvious breaks (i.e., unknown) as a major break cause, similar to the case of pressroom breaks.



Figure 9. Break frequency statistics in a Japanese paper mill in 1990s [97].

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Process causes for web breaks have been sought by using phenomenological approaches, such as principal component analyses and neural network analyses (e.g., [100–103]). For example, Table 1 shows a list of on-line process variables and off-line measurements investigated for web breaks in a newsprint mill [103].

Note that some of the variables included here were kraft content (SBKP ratio), macroscopic defects, and dry strength properties, which are widely believed to be the principal factors controlling web breaks by the industry. The results are given in Table 2. The neural network analyses identified five variables that contributed

	On-line sensors	15	Couch vacuum	29	Alum
1	SBKP freeness	16	Dryer steam pressure	30	Retention aid
2	GP freeness	17	Wet-web moisture	31	SBKP ratio
3	TMP freeness	18	Basis weight	32	GP ratio
4	1 DIP freeness	19	Paper moisture	33	TMP ratio
5	2 DIP freeness	20	Caliper	34	1 DIP ratio
6	Inlet pH	21	Spot (large)	35	2 DIP ratio
7	Inlet temperature	22	Spot (small)		Lab Measurements
8	Inlet conductivity	23	Black spot (large)	36	Tear strength
9	Inlet zeta potential	24	Black spot (medium)	37	Tensile strength
10	Inlet consistency	25	2P/3P draw	38	Stretch
11	White water consistency	26	3P/1D draw	39	Brightness
12	Inlet pressure	27	Machine speed	40	Opacity
13	Wire suction-box vacuum	28	Broke ratio	41	Stuff-box freeness
14	Pick-up felt vacuum				

 Table 1. Process variables investigated for principal component and neural network analyses [97]

 Table 2.
 Main process factors affecting paper machine breaks [97]

Variables	Effect on break	Interpretation
White water consistency	++	Retention, cleanliness, drainage
Inlet temperature		Drainage, higher solids
Stuff box freeness		Drainage, higher solids
TMP freeness	++	Wet web strength
Machine speed	+	Tension

most to web breaks. The symbol + (or ++) means that an increase in the variable increased web breaks modestly (or a great deal). One interesting observation is that three of the five variables extracted were closely related to drainage: reduced drainage (or lower solids content) clearly increased break tendency. On the other hand, increased freeness of TMP tended to increase breaks. The latter was interpreted as reduced wet strength. The machine speed is a well-known factor influencing web breaks, partly due to the increased draw, as will be discussed later. Most interestingly, none of the factors that have been perceived to control web runnability, such as defects, kraft content, and dry strength, were extracted as main factors in this analysis.

These observations are certainly providing good insights of what is happening in paper machine. However, a clearer picture may be obtained by looking at the problem from variability and non-uniformity view point. First, as we discussed in the section of web tension uniformity, the presence of non-uniform web tension variation across the machine is the biggest cause for web fluttering (vibration) in the open draw section. A typical reaction of the operator to edge-fluttering is to increase draw. If not, the machine creates wrinkles, which is another cause of breaks. On the other hand, if draw is increased to eliminate fluttering, there is more vulnerability to breaks because of increased tension. Either way, solving web tension non-uniformity across the machine width is the first and fundamental step to resolve break issues. The basic cause of web tension non-uniformity is the moisture and moisture history variation across the machine width, as discussed earlier.

Open draw, which is still present in most of the current press/dryer configurations, is most controversial from the point of runnability. This is the place where tension varies even at a constant draw. It is also the place where tension and wet web properties interact. Since the early days of paper machine research, open draw has attracted much attention of both theoretical and experimental studies (e.g., [104–115]). The latest non-steady state analyses of open draw with varying web properties showed an interesting interaction between the variability of wet web properties and tension variability. Figure 10 shows web strain in the open draw section as a function of time.

Since the strain is not uniform along the length of the span (i.e., increasing along the length of open draw section), the maximum strain within the span is plotted. In this example, wet web is subjected to a 15% stepwise decrease of its elastic modulus for different time durations, 3, 4, and 5 seconds [106–107]. Such elastic modulus reduction may be realized by a sudden increase in moisture content by process disturbances. As elastic modulus decreases suddenly, web strain shoots up because the web detachment from the preceding roll is delayed. For the duration of 3 and 4 seconds, such disturbances of web strain are subsided eventually as elastic modulus regains the original value. However, in the case of



Figure 10. Strain variation due to a 15% decrease in elastic constant at a machine speed of 1600 m/min [107].

the 5-second duration, the web strain no longer returns to the original value (3%) but continues to increase, implying imminent break. This example illustrates how the variability of wet web properties could induces tension variations even if draw is kept constant. At the same time, it also indicates that the variation of any factor that affects wet web elastic modulus, most notably moisture content (or solids content), can induce tension variations.

Another obvious factor contributing paper machine runnability is wet web strength. The studies on the fundamental mechanisms of wet web failure and the measurements of wet web strength have a long history (e.g., [116–122]) in papermaking research. Wet strength of today's mixed furnishes, containing mechanical, chemical and recycled fibres, together with fillers and various wet-end additives, has also been the main focus in the area (e.g., [123–125]). However, wet strength is normally measured in an offline (static) mode in the laboratory. However, there is a question whether a running wet web behaves in the same way as in a static mode. Recently wet web behavior has been determined also in a dynamic mode [126]. In this mode, by applying a sudden strain, like in an open draw section, web tension relaxes, and this retention capacity of web tension has been proposed as another important property of wet sheets that may contributes to paper machine runnability [126].

From the point of variability, a natural question is how much wet web strength varies during papermaking operation. Unfortunately, there has been no direct measurement reported in the literature, to the author's knowledge. However, the most prominent factor that controls wet strength is moisture content or solids content [121–122]. This factor is affected by the drainage property of the stock (concentration, freeness, fibre swelling, fines content, retention aids, etc.) as well as the machine's drainage capacity (vacuum, press loading, press configuration, etc.). Therefore, if the moisture content of wet web varies both spatially and temporarily, this will directly affect wet web strength variability. This will also affect wet web density and elastic modulus, in a negative way, from the point of the stability of the open draw section, as discussed above [105]. Unfortunately, moisture profiles in the cross machine direction and the machine direction in the wet-end has not routinely been measured until recently. A new sensor system for full-sheet moisture measurements has been developed for monitoring a complete MD-CD profile in papermaking process [127]. Figure 11 clearly showed a nonuniform CD moisture profile in the wet-end as well as periodic variations in the machine direction [127].



Figure 11. Moisture variation in the machine and cross-machine directions [127].

3.4 Out-of-plane dimensional stability: Fluting and cockling

Since the inception of papermaking, fluting and cockling have been persisting in the industry without much indication of the resolution of the problems (for example, [128–130]). The problems are typically seen after printing (heatset offset and inkjet printing) as well as after drying of paper making. Fluting is a corrugation-like, out-of-plane deformation oriented in the machine direction, and its wave length in the cross machine direction is typically one or two centimeters. Cockling is, on the other hand, more random features without any specific orientation direction [131].

Fundamental mechanisms of fluting and cockling are still somewhat controversial. As beautifully demonstrated in the earlier work by Brecht with a simple experiment [128], cockle can be created by producing local variations of drying "histories". If paper sheet has some wet and dry areas during drying, these areas develop residual strains differently, and then buckle after drying is completed, causing cockles. Fluting, on the other hand, has been investigated more specific to a heatset offset printing process [132–134]. The most basic ingredients that are required to cause fluting were tension, heat, and moisture in the sheet, and ink promotes fluting amplitude as well as its retention [133, 135]. Accordingly various mechanisms for fluting have been proposed. If paper is assumed to be uniform, then the mechanisms proposed are global buckling due to tension [136-138], nonuniform applications of ink/moisture [137-141], and drying heat (air impingement) [134, 136]. These mechanisms tend to predict much larger wave length of fluting than what were observed in printing. However, if paper is assumed to be non-uniform, local buckling can occur. One example of non-uniformity is local variations of fibre orientation (its direction and degree). This structural variation could trigger local variations of hygroexpansion, and thus local buckling [142]. Extensive numerical analyses were performed, and the results exhibited cocklinglike features [143–144]. However, in order for induce significant magnitude of cockling, this mechanism required a large amount of moisture change, which could happen only in the drying process of papermaking rather than printing. Local two-sidedness of fibre orientation and moisture was shown to have potential to explain cockling phenomena [145–146], although direct experimental verification of this mechanism is difficult. The last mechanism is local variations of moisture content that cause local variations of hygroexpansion. In this mechanism, the local variation of moisture required for producing significant fluting/ cockling is in the order of 0.8% or more, which is quire realistic [135]. (See Fig. 12 [135].) It was proposed that such moisture variations can be induced by local variations of permeability [135].

At this stage, there has been no conclusive result that supports a specific mechanism. However, there have been some anecdotes accumulated from various



Figure 12. Fluting pattern predicted from random moisture variations [135].

pilot-scale, mill and press trials. A specific structure of flocs (coherent flow structure) created in vane tips in the hydraulic headbox has been suggested as a potential cause of cockles [147]. However, there has been no identification of specific headbox types that cause cockling from fields. Formation also has been studied in many mill trials. Generally no correlation has been found between cockles and formation as defined by various routine measurements (for example [132]). On-line calendaring has been known to have a negative impact on cockling and fluting. However, by over-drying the sheet and re-moisturising it before calendaring, the effect can be reduced significantly. This observation points toward micro-scale moisture variations created in papermaking process as a potential culprit of the problem. The variability and non-uniformity of moisture content in this length scale (millimeter scales) are still a largely unknown territory in papermaking research.

3.5 Mechanical performance of corrugated boxes

Corrugated box is probably one of a few very successful examples of the application of fibre network as a *structural* member. In general today's boxes are well designed, and perform in the fields with very few problems. In some occasions, there might be box failures. In such cases, the suppliers may change a design parameter to increase strength, or may simply pay the penalty. A real challenge may be the persistent, sustainability packaging demands from the market, i.e., reduced packaging, light-weighting, and thus increased strength. (Excellent reviews on compression strength of corrugated box are recently given in [148–149].)

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What is the problem? The problem may be more fundamental. Corrugated boxes are typically designed by a safety factor, i.e., a ratio of box strength to intended applied load. (Note that there are many slightly different definitions of the safety factor in different industries and different disciplines.) The safety factor is always taken as more than unity, because of the expected degradations of the box (time-dependency/creep and humidity/temperature fluctuations) and occasional abusive loads in end-use. The values of the safety factor for boxes are typically 2-7 and sometimes even 30, while the aircraft and space craft use 1.2-3.0 depending on the materials. Clearly corrugated boxes tend to be over-designed with a generally higher safety factor than other structural members/materials. This may be simply due to the fact that the materials are less expensive and it is easier to raise the safety factor to avoid end-use problems. It may also imply that fibre-based materials and box structures have more uncertainty than other counterparts. Should one do something on this? This question is not trivial, because the industry has been working on the strength enhancement in its whole history, and the strength specification is most fundamental, directly affecting the industry's cost structure of manufacturing.

Before answering the question, we will first look at, what we call, "end-use performance" of corrugated box. A safety factor is a practical but an approximate way of translating strength into end-use performance. However, end-use conditions are vastly different from those conditions used for measuring strength in the laboratory. For example, a time scale for strength testing is typically seconds or minutes, whereas it is days and months in end-use. Load levels in end-use are varying but normally much lower than ultimate strength. Temperature and humidity are fluctuating, but are normally kept constant in strength testing. Therefore, it is not surprising that strength may not exactly represent end-use performance, since the latter is a more multi-faceted property.

Needs for testing boxes in a more realistic condition have been recognized for many years. For example, Kellicutt and Land [150] performed creep tests at different loads to determine lifetime of box, the time at which the box fails. They reported that lifetime obviously increases with decreasing load, but it is a very sensitive function of load applied. (See Fig.13.) This means that small variability of load applied in end-use has an immediate impact on the performance of the box. Secondly, the researchers also recognised that, even at the same load, lifetime varied immensely. This was reconfirmed by many other researchers [151–153]. For example, Koning and Stern [151] reported that, when the boxes were tested at a 50% of the maximum strength, lifetime varied 125 hours to 2817 hours. In the literature, we find typical values of the coefficient of variation (COV) are in the range of 70% to 90% [154]! This should be compared with the corresponding COV values of only 5–8% for the standard box compression test [155]. It should also be noted that these tests were performed under nominally the same



Figure 13. Applied load vs. creep life time for corrugated boxes. Reconstructed from [150].

environmental condition, unlike end-use conditions where temperature and humidity are constantly fluctuating. A recent creep failure study of corrugated boxes showed a dramatic effect of such environmental conditions [156]. About 30 corrugated boxes were subjected to 500 N of load under two conditions: one is at temperature around 0 degree with relative humidity varying between 70% to 90% (Condition 1), and the other is at temperature around 20 degrees with relative humidity between 60% to 90% (Condition 2). Figure 14 shows cumulative distributions obtained for these two environmental conditions. The cumulative distributions are plotted in Weibull form. By moving from Condition 1 to Condition 2, average lifetime increased from 11 days to 21 days. One can also find two outliers for the tests performed under Condition 2, showing only 2.5 days of creep life time with its average of 21 days. Because of this enormous scatter of lifetime data, many researchers avoided direct testing of creep failure, but measured secondary creep rate as a function of load. The idea behind is based on the empirical relation that Monkman and Grant [157] found for metal creep: creep lifetime is inversely proportional to secondary creep rate. (A critical review of creep deformation and life time analyses are given in [158].) Even with such data handling, the plots still showed a large scatter of up to 50% when expressed with COV.



Figure 14. Distribution of creep life time plotted in Weibull format. Reconstructed from [156]. F(t): Cumulative distribution of creep life time.

A natural question is what is causing such extreme variability of creep life time of corrugated box. There is surprisingly very little information in the literature. It is partly because of the difficulty of performing lifetime testing under controlled conditions for a prolonged period (months) and partly because of its enormous variability that have discouraged many researchers and engineers to tackle the problem itself.

An obvious speculation is that defects created in the corrugated structures during converting operation may be causing this variability. Unfortunately there is no statistically significant data available in the literature. However, an interesting observation was made by Charmes [159] that artificially crushing the corrugated boards in the thickness direction drastically decreased (average) creep life time of the boxes, while box strength (short-term test) received a rather modest effect of crushing. Therefore, converting defects can certainly contribute to creep lifetime degradation. The recent study showed that linerboard exhibits even more variability in creep lifetime than box [160].

The last and most important question may be what to do with this variability. This is one of the hardest questions left in the area of corrugated packaging. However, the problem has an extreme resemblance to the runnability problems discussed earlier. Box failure is the result of interactions between the variability in end-use conditions (load and environment) and the variability of box structures, converting defects and component boards, while web breaks in printing house and paper machine is the result of interactions between the variability of tension and the variability of paper strength. Interestingly both are statistical failure and an extreme statistics phenomenon. With this analogy, a formal approach has been proposed based on recent progresses in statistical physics [160].

4. MORE COMPLEXITY AND FUTURE

As seen in the above discussions, many of the (difficult) performance issues are closely related to variability and non-uniformity of both paper properties and enduse conditions (Fig. 15). The paper properties in the cases mentioned above included moisture content, tensile strength, hygroexpansivity, elastic stiffness, residual strain, permeability, and long-term durability, all of which vary with both space and time. These properties are obviously the results of variability in papermaking process. However, at this moment, our knowledge on the variability of these paper properties in relation to the papermaking processes is still limited. What we have progressed so far is to understand time-averages of those properties, such as tensile stiffness, strength and stretch, in a large scale in the crossmachine direction [89–93, 161–163]. In other words, we still don't know what are causing the time variations of the paper properties, both at low and high frequencies, and also the spatial variations in the range of a few millimeters.



Figure 15. Product-process chain as a complex system.

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Another important aspect of the product performance issues is that they are never a single paper property problem, but is a *systems* problem. For example, paper machine runnability is never a single problem of wet strength of paper sheet, but is the problem of the entire pulp/paper making processes and how they are operated. Figure 15 depicts a systemic view of the problem. Performance is normally controlled by several paper properties, as mentioned earlier. It is also controlled by end-use conditions which the paper is subjected to. (We call it here "end-use conditions", but it could be paper machine, coaters, corrugators, and printing presses.) Moreover, the variables in the paper property group are not independent of those in the end-use condition group (Fig. 15), but they interact each other. For example, a baggy roll (paper properties) induces tension variations (end-use conditions), while temperature and relative humidity (end-use conditions) affect web strain, stiffness and strength variations (paper properties). That is, both variables are coupled. Naturally all paper properties are also coupled with each other, as they are functions of almost any variables present in the manufacturing process, such as fines content, jet/wire speed ratio, press loading, etc. In the manufacturing process, there are thousands of control loops that also interact each other. (An added problem is that many of those control loops are not necessarily functioning properly, sometimes creating more variability [8, 164].) Lastly the relationships between all of these coupled variables are not necessarily linear but are often highly nonlinear. In other words, if one amplifies the input by three folds, what we see in the output may not be a three-fold increase, but may be 100 times or one thousands of the input value. Therefore, as we see the product performance issues as such a system, we may find that it is characterized by the following three attributes: (1) multi-variables, not a few but hundreds or thousands of variables, (2) those variables are highly *coupled*, and (3) each relationship is often nonlinear. In fact, such a system is called "complex system". It is complex in layman's terms, but also complex as defined in complexity science (for example [165–167]).

Although a rigorous mathematical definition is still in debate, complex systems exhibit some unique interesting features. One is the butterfly effect: several weeks before a hurricane occurred in Texas, a butterfly in Amazon flapped its wings. This is a metaphor for the extremely sensitive dependence on initial conditions that sometimes appears in nonlinear dynamics systems (for example, [168]). In other words, a small change in the initial conditions causes later an unexpectedly large change in an unexpectedly remote place. This example may not be completely an unfamiliar event for many papermakers. We sometimes experience disastrous quality problems in the market place, when they make seemingly minor changes in process conditions (e.g., a changing a dosage point of retention aids, increasing machine speed, etc.) As the system becomes more and more complex both in

manufacturing and also in the market (See Fig. 15), one of the consequences may be more butterfly effects.

Another somewhat related characteristic of complex systems is the law of unintended consequences. In the United States, the promotion of (green) biofuel resulted in the increases in food prices, particularly beef, pork, and chicken. This is because, in the United States, the promotion of biofuel means the production of ethanol distilled from fermented corn. This initiative encouraged farmers to grow corn for fuel production than for foods for humans and for animals, resulting in price increases of human foods, as corn is used as additives as well as feed stock for animals. Such unintended consequences are numerous in politics, as the human society is essentially a huge, multi-variable, highly-coupled, adaptive system of agents (people), and it is difficult to control with a still much simpler system (politics) [169]. Similar stories abound in the industry. For example, because of the market slump in early 2000, a production curtailment measure was taken in a paper mill in Canada, by taking more down time for maintenance and repairs. After one month later, the production in the mill increased unintentionally. This example typically shows that production efficiency and machine runnability are a complex system problem. In the 70s and 80s, North American and European industries tried to create competitive advantages in productivity and production efficiency by developing wider and faster paper machines. The technical objectives have been achieved. However, the consequence was that it created competitive disadvantages. This technical development increased the capital cost, making the matured North American and European industries more difficult to adapt the new technology, whereas emerging countries who adapted the latest technology immediately received a maximum benefit.

Complexity science is still an emerging scientific discipline, but is no longer in an academic circle dominated by celebrated scientists. It is an industrial reality and part of our everyday life. In the future we may see more and more butterfly effects and unintended consequences, because the industry's production systems will be bigger, more integrated, more networked, and more tightly coupled with the market place. Variability and non-uniformity in product and process are just a manifestation of the very nature of complex systems. In order to resolve many of the current industry challenges, it is, therefore, most important to take a systems approach. The systems approach here is not to establish a phenomenological (or empirical) relation between input and output variables of the system, but, by adhering to the first principles as much as possible, to understand *collective* behavior of a whole system. This subject has been explored actively in multidisciplinary areas, and various computational tools and new concepts are being developed (for example, [166, 170]).

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Transcription of Discussion

VARIABILITY, NON- UNIFORMITY, AND COMPLEXITY: FROM PRODUCT TO PROCESS

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Daniel Söderberg KTH and Innventia (from the chair)

Looking at the study done at Nippon Paper⁴, that was done using principal component anaysis (PCA), I think, and it points out why we are here, doesn't it? You do a lot of correlations between things and then you want to draw conclusions on the effects. I think they are wrong. Because they have a BelBaie 2 former on the machine and, when they are using the blade section heavily, they get increased concentration in the white water and the sheet is damaged – that's why you get the weak sheet. You need to have the fundamental understanding to know how it behaves, don't you?

Tetsu Uesaka

Yes, of course, I am not ignoring any of the fundamental understanding, and obviously, as I said, these data are from phenomenological studies, and interpretation could be stated in many ways but it is very difficult to prove a conclusion completely. Because a machine break is an extreme statistics problem: you need to collect fifty thousand events. Therefore, you can make any interpretation, but proof is not possible. That is why we need a different approach and I am not denying the importance of the fundamental studies, just saying that phenomenological studies are a support for them.

⁴T. Miyanishi and H. Shimada, "Using neural networks to diagnose web breaks on a newsprint paper machine". Tappi Journal, 1998. 81(9): 163–170.